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Control Theoretical Modeling of Transient Behavior of Production Planning and Control: A Review

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Abstract

To remain competitive, manufacturers need to adapt to increasingly dynamic and turbulent markets; therefore, production engineers and business managers need tools for mathematically modeling, analyzing and designing agile and changeable production systems that incorporate policies that are robust in the presence of disturbances and mitigate the negative impacts of turbulence in the production environment. The spectrum of potential contributions of control theory to understanding the dynamic behavior of production systems in the presence of turbulence is broad. In this paper, the focus is on classical control theoretical modeling of the transient behavior and fundamental dynamics of production planning and control, which generally is considered to include scheduling, sequencing, loading and controlling. Publications in this area in recent years are reviewed, with contributions reported in publications of the CIRP (International Academy for Production Research) receiving particular emphasis.

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1. Introduction

To remain competitive, manufacturers need to adapt to increasingly dynamic and turbulent markets and design production systems and policies that are changeable and respond with agility [1]. Methodologies therefore are needed that enable production engineers and business managers to mathematically model, analyze, and design agile and changeable production systems and supply chains that incorporate strategies and policies that are robust in the presence of disturbances and mitigate the negative impacts of turbulence in the production environment. Nowadays, production engineers construct models in computational form: analytical models represent a mathematical abstraction of the real manufacturing systems, and a set of equations is formulated that summarizes aggregate dynamic behavior; simulation models are experimental and model events that would occur in real production systems [2].

Several reviews have been published in the past that address various aspects of the application of control theory in analysis and design of dynamic behavior of production systems and supply chains: Ortega and Lin (2004) [3] reviewed control theory applications in production–inventory problems; Sarimveis et al. (2008) [4] reviewed dynamic modeling and control of supply chain systems; and Ivanov et al. (2012) [5] reviewed applicability of optimal control theory to adaptive supply chain planning and scheduling. These reviews make it clear that the spectrum of potential applications of control theory in analyzing many aspects of production systems and their management is large, and that the potential contributions of control theory to understanding the dynamics of these systems are significant.

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In this paper, the focus is on the use of classical control theory in analyzing the transient behavior of Production Planning and Control (PPC), which generally is considered to include scheduling and sequencing (plan when), loading (plan how much) and controlling (follow plans) [6]. Sarimveis et al. [4] and Ivanov et al. [5] thoroughly review supply chain applications (this is not addressed further in this paper). A number of authors have published in this area in recent years, including many contributions reported in publications of the CIRP (International Academy for Production Research). These receive particular emphasis in this paper. Non-control-theoretical methods of modeling production planning and control systems will be briefly summarized first. Then, an overview of classical control theoretical analysis will be presented. The focus on classical control theory is deliberate in this paper because its application is within reach of practicing production engineers who often have had at least an introductory exposure to the topic in their undergraduate-level, graduate-level or professional education. (Addressing the known limitations of classical control theory, significantly more mathematically advanced theories have been developed in areas such as nonlinear control, optimal control, stochastic control, adaptive control, robust control, H_∞ control, etc.; these are outside the scope of this paper.) Summaries of contributions to control theoretical analysis of production planning and control systems then are presented. Figures, particularly block diagrams reproduced from referenced publications, are included to illustrate the nature of approaches taken. Readers are encouraged to refer to these publications for details regarding dynamic models, key variables, behavior observed, conclusions, etc.

2. Non Control Theoretical Modeling Methods

Computer simulation can produce high-fidelity predictions of the transient behavior of production planning and control systems. Discrete event simulation (DES) is a common tool for detailed modeling of production systems. Queues, workstations, etc. are individually modeled, with a focus on events such as the movement of orders or their contents between workstations and queues. Simulations often are driven by inputs with probabilistic distributions, and system behavior in response to these inputs is then characterized statistically using simulation results. Significant amounts of time are often required to develop DES models, run simulations, and analyze the results. There is no analytical solution that can be used for design purposes; for example, control laws or policies for release of orders into a system or adjusting production capacity cannot be directly analytically designed using simulation results. Instead, large numbers of iterative simulation experiments are typically used to characterize observed dynamic behavior and subsequently select good control policies [7] [8].

Queuing network analysis is another commonly used method for evaluating performance of production systems [9]. A network of queues is modeled in which orders, workpieces, etc. arrive, wait until they are processed, and then move on to the next processing step. Queuing network model inputs are defined by steady-state probability distributions. Queuing models allow, for example, a system controller to observe a queue at a workstation and change its control settings. However, the models are applicable to a limited number of queue disciplines, and the transient behavior of production systems rather than their steady state behavior often is of interest. Furthermore, the structure of real production systems can be too complex to analytically represent using queuing network analysis [2].

The Petri net is a graph representation that can be applied in modeling PPC systems [10] [11]. A Petri net is constructed using places, transitions, and arcs [12]. Tokens circulate through the network according to transitions that may depend upon conditions such as the number of tokens in its input places; a transition creates tokens in its output places. Petri nets have been used, for example, to analyze deadlocks in production systems [13] and to find best schedules [14].

System Dynamics is a technique developed by Forrester [15] for building dynamic models. Loop diagrams and stock-and-flow diagrams are used to describe information, control and flow of orders, workpieces, etc. System dynamics applies the concept of feedback loops in representing a broad range of physical and social systems. The technique is simulation-based and typically does not provide analytical solutions that could be used to identify fundamental transient system dynamic characteristics. As with DES, numerous trial-and-error simulations may be needed to characterize transient system behavior and design control laws and policies.

3. Control Theoretical Modeling Methods

The modeling methods summarized above do not directly predict the fundamental dynamic characteristics of production systems operating under transient conditions. Characteristics of interest can include the time required for a system to return to normal operation after a disturbance such as a rush order or equipment failure (settling time), overshooting and possible tendency of variables such lead times to oscillate (damping), and the range disturbance frequencies over which performance deviations are significant (bandwidth; typically, responses are larger for low frequency disturbances and smaller for high frequency disturbances, and the bandwidth or cutoff frequency is a frequency that characterizes the relative boundary between high and low frequency behavior for a given system). Such fundamental dynamic characteristics can be directly obtained from classical control theoretical models, and the tools of control engineering can be used to directly design control laws and policies; therefore, there has been much interest in the use of classical control theory in modeling production planning and control systems.

Classical control analysis and design methods are characterized by the use of continuous time (Laplace transforms) or discrete time (Z-transforms) transfer functions [16] [17] in modeling the dynamics of production systems. These transformations and some of their properties are listed in Table 1. Linear, time-invariant differential equations and difference equations in the cases, respectively, of continuous physical relationships and discrete physical relationships (such as equipment controlled by computers), are transformed to obtain cause-effect transfer functions and equations. These can be incorporated into block diagrams that represent interconnections and interrelationships between system